

1 CFC₁₃ (CFC-11): UV absorption spectrum temperature dependence measurements and the 2 impact on atmospheric lifetime and uncertainty

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10 **Key Points:** * Uncertainty in the CFC-11 photolysis lifetime was reduced from ~25 to 4%
11 * Previous recommendations overestimated the T-dependence of the UV spectrum
12 * The lifetime and GWP of CFC-11 are less than previously reported

13 CFCl₃ (CFC-11) is both an atmospheric ozone-depleting and potent greenhouse gas that
14 is removed primarily via stratospheric UV photolysis. Uncertainty in the temperature
15 dependence of its UV absorption spectrum is a significant contributing factor to the overall
16 uncertainty in its global lifetime and, thus, model calculations of stratospheric ozone recovery
17 and climate change. In this work, the CFC-11 UV absorption spectrum was measured over a
18 range of wavelength (184.95–230 nm) and temperature (216–296 K). We report a spectrum
19 temperature dependence that is less than currently recommended for use in atmospheric models.
20 The impact on its atmospheric lifetime was quantified using a 2-D model and the spectrum
21 parameterization developed in this work. The calculated global annually averaged lifetime was
22 58.1 ± 0.7 years (2σ uncertainty due solely to the spectrum uncertainty). The lifetime is slightly
23 reduced and the uncertainty significantly reduced from that obtained using current spectrum
24 recommendations.

25 **Key Words:** Ozone depleting substance, chlorofluorocarbon, photolysis, UV cross section

26 **1. Introduction**

27 Accurate knowledge of the atmospheric lifetimes of ozone depleting substances (ODSs)
28 is important to the understanding of their atmospheric abundance, emissions, and future
29 environmental impacts as well as the calculation of ozone depleting (ODPs) and global warming
30 potentials (GWP). CFCl_3 (CFC-11) is a key long-lived man-made ODS that is also a potent
31 greenhouse gas (GHG) [WMO, 2011] whose production was phased out under the Montreal
32 Protocol and its subsequent amendments. CFC-11 is of particular importance due to its
33 atmospheric abundance and the fact that it is the reference substance to which ODPs for all other
34 ODSs are scaled. The atmospheric abundance of CFC-11 is presently decreasing [WMO, 2011]
35 from a maximum mixing ratio of ~ 270 ppt in the early 1990s to a present day value of ~ 240 ppt;
36 CFC-11 accounts for 22% of the present day stratospheric chlorine. CFC-11 is primarily
37 removed in the stratosphere by UV photolysis at wavelengths between 190 and 230 nm and to a
38 lesser extent by gas-phase reaction with $\text{O}(\text{¹D})$ atoms.

39 The room temperature UV absorption spectrum, $\sigma(\lambda, 298 \text{ K})$, of CFC-11 is reasonably
40 well established, $\pm 5\%$, over the wavelength range most critical to atmospheric photolysis (see
41 Sander *et al.* [2011] and references therein). However, the spectrum temperature dependence,
42 which is key to determining its stratospheric photolysis rate, is less certain and the level of
43 uncertainty contributes substantially to the uncertainty in determining the global lifetime of CFC-
44 11 [SPARC, 2013]. The CFC-11 absorption spectrum temperature dependence has been reported
45 in studies by Bass and Ledford [1976] (186–230 nm, 222–298 K), Chou *et al.* [1977] (185–226
46 nm, 213–296 K), Hubrich *et al.* [1977] (158–260 nm, 208 and 298 K), Simon *et al.* [1988] (174–
47 230 nm, 225–295 K), and Mérienne *et al.* [1990] (200–238 nm, 220–296 K) over the range of
48 wavelengths and temperatures given in parentheses. The absorption spectrum parameterization
49 reported in the Simon *et al.* [1988] study is currently recommended for use in atmospheric
50 models in Sander *et al.* [2011] due, in part, to the combined wavelength and temperature range
51 coverage of the dataset. Discrepancies among the available datasets, however, led the recent
52 SPARC [2013] lifetime report to recommend a substantial uncertainty in the low-temperature
53 spectrum, i.e., approximately a $\pm 25\%$ uncertainty in $\sigma(\lambda, 220 \text{ K})$.

54 The SPARC [2013] lifetime report recommends a global steady-state (year 2000) lifetime
55 for CFC-11 of 52 years with 2σ uncertainties that lead to lifetimes in the range 43 to 67 years
56 (see discussion in SPARC [2013]). The recommended lifetime and range are based on a
57 combination of model calculations and derivations from atmospheric observations. The range in
58 the recommended lifetime has several contributing factors due to uncertainties in both the model
59 and observationally based lifetimes, including the uncertainty in the UV absorption spectrum

[Minschwaner *et al.*, 2013; Rigby *et al.*, 2013; SPARC, 2013]. The present level of CFC-11 lifetime uncertainty is significant and directly impacts the ability to model climate change and climate-chemistry coupling scenarios. An objective of the present work was to constrain the UV spectrum of CFC-11 further, particularly at temperatures most relevant to stratospheric photolysis, and, thus, its lifetime and uncertainty.

In this work the UV absorption spectrum of CFC-11 was measured at 216, 235, 254, 274, and 296 K at 24 discrete wavelengths between 184.950 and 230 nm. The present results are compared with previous temperature dependent studies mentioned above and the discrepancies are discussed. A parameterization of $\sigma(\lambda, T)$ was developed from our work for use in atmospheric models. The NASA Goddard Space Flight Center (GSFC) 2-D coupled chemistry-radiation-dynamics model [Fleming *et al.*, 2011] was used to evaluate the atmospheric photolysis, local and global annually averaged lifetimes of CFC-11 as well as the range of lifetimes obtained based solely on the estimated uncertainty in $\sigma(\lambda, T)$.

2. Experimental Details

The apparatus used in this work was similar to that used in recent studies from this laboratory [e.g. Papadimitriou *et al.*, 2013]. In brief, the apparatus consisted of a 30 W deuterium (D_2) lamp, whose output was collimated through a 90.4 ± 0.3 cm long, jacketed absorption cell and directed onto the entrance slit of a 0.25 m monochromator with a photomultiplier tube detector. The beam-path outside of the absorption cell and monochromator were purged with N_2 . The monochromator wavelength was calibrated using atomic lamps to ± 0.1 nm and the resolution was ~ 1 nm (FWHM). Additional measurements were made at 184.950, 213.856, and 228.802 nm using Hg, Zn, and Cd atomic lamp light sources, respectively, with a photodiode detector coupled with narrow band-pass filters. The absorption cell temperature was maintained by circulating fluid from a temperature-regulated reservoir through the cell jacket. The gas temperature was measured using a thermocouple inserted at both ends of the absorption cell and was accurate to ~ 1 K over the temperature range of this study.

Absorption cross sections, $\sigma(\lambda, T)$, were determined using the Beer's law

$$A(\lambda) = -\ln[I(\lambda)/I_0(\lambda)] = \sigma(\lambda, T) \times L \times [\text{CFC-11}] \quad (\text{I})$$

where A is absorbance at wavelength λ , $I(\lambda)$ and $I_0(\lambda)$ are the measured light intensities in the presence and absence of sample, L is the pathlength of the absorption cell. Measurements were performed under static conditions and [CFC-11] was determined from absolute pressure measurements using the ideal gas law. Absorbance was measured for a range of concentrations, at least 10 concentrations were used in each measurement, and cross sections were determined from a linear least-squares fit of A against [CFC-11]. Signals were stable to better than 0.5% and

94 $I_0(\lambda)$ values were measured at the beginning and end of an experiment agreed to within 0.5%,
95 corresponding to an absorbance uncertainty of less than ~0.005.

96 CFC-11 (99.7%) samples were purified in freeze-pump-thaw cycles before use. He
97 (UHP, 99.999%) was used as supplied. Gas mixtures, prepared manometrically in 12 L Pyrex
98 bulbs, with 0.0022, 0.0218, and 0.1836 mixing ratios of CFC-11 in He (accurate to 1%) were
99 used to introduce the sample into the absorption cell. Pressures were measured using calibrated
100 10, 100, and 1000 Torr capacitance manometers.

101 3. Results and Discussion

102 Gas-phase UV absorption cross sections, $\sigma(\lambda,T)$, for CFC-11 were determined at 24
103 discrete wavelengths over the range 184.95–230 nm at 216, 235, 254, 274, and 296 K. $\sigma(\lambda,T)$
104 values are summarized in Tables S1 and S2 in the supplementary material and plotted in Figure
105 1. $\sigma(\lambda,T)$ values shown in Figure 1 are average values when multiple measurements were
106 performed. The CFC-11 UV absorption spectrum has continuous absorption from the shortest to
107 the longest wavelength included in this study. $\sigma(\lambda,T)$ decreases toward longer wavelengths from
108 a maximum at 184.950 nm with the decrease nearly exponential at wavelengths greater than
109 ~210 nm. The true spectrum maximum lies at a wavelength shorter than included in this work;
110 *Simon et al.* [1988] report a maximum near 176 nm. However, photolysis at wavelengths less
111 than ~190 nm is relatively unimportant as an atmospheric loss process (Figure 2). The peak
112 transition has been assigned to a (C–Cl)* \leftarrow Cl transition [*Sandorfy*, 1976].

113 A temperature dependence of the CFC-11 absorption spectrum, Figure 1, was observed
114 across much of the absorption spectrum, but was weak near 196 nm. At wavelengths greater
115 than 196 nm, the cross sections decreased with decreasing temperature. At wavelengths less than
116 196 nm a weak increase in cross section was observed with decreasing temperature. The
117 strongest temperature dependence was observed at the longest wavelengths of this study, e.g. the
118 cross section decreases by ~52% between 296 and 216 K at 230 nm.

119 The measurement precision was high over the wavelength range studied, typically less
120 than 1% uncertainty. Replicate measurements were made in many cases that included using
121 different sample mixing ratios and different ranges of absorbance as well as different
122 experimental parameters (e.g. light intensity and optical filtering). In each case, the measured
123 absorption obeyed Beer's law. The measurement reliability was also tested by comparing data
124 obtained with the monochromator at the wavelength of the atomic lamps. The 296 K
125 measurements at 213.95 nm (Zn line) agreed to better than 1%, while the difference at 228.802
126 nm (Cd line) was ~4%, with the Cd lamp measurements being greater.

127 The uncertainties reported in Table S1 are 2σ from the precision of the Beer's law fits to
128 the data. The overall 2σ uncertainty including estimated systematic errors of the measurement is
129 estimated to be 4% at all wavelengths included in this study.

130 **3.1 CFC-11 UV spectrum parameterization.** On the basis of the present $\sigma(\lambda, T)$ measurements,
131 a spectrum parameterization was developed using the empirical expression given in Table 1.
132 The fit parameters are given in Table 1 and spectra calculated from this expression are included
133 in Figure 1 for comparison with the experimental data. The parameterization fits the
134 experimental data to within 2% between 192–222 nm, lower panel in Figure 1. The
135 parameterization is valid over the wavelength range 190–230 nm (optimized for 192–230 nm)
136 and over the temperature range (216–296 K) of the experimental data. Extrapolation outside the
137 range of the experimental data may lead to systematic errors.

138 **3.2 Comparison with previous studies.** The $\sigma(\lambda, 296 \text{ K})$ results obtained in this work are in
139 agreement with the recommended room temperature absorption cross section data given in
140 *Sander et al.* [2011] to better than 7% between 190 and 230 nm. Results from all previous
141 temperature-dependent studies are compared with the present results in Figure 1. The *Simon et al.*
142 [1988] study is assumed to supersede the *Vanlaethem-Meurée et al.* [1978] study from the
143 same group. Overall, the agreement among the various temperature dependent studies is rather
144 poor, with differences on the order of $\pm 10\text{--}20\%$. The present results are most consistent with the
145 data of *Chou et al.* [1977], where the agreement is to within 5%, or better, over most of the
146 wavelength range; the differences are somewhat greater for some of the longer wavelength data
147 points, but still agree to within 10%. The work of *Mérienne et al.* [1990] is in reasonable
148 agreement (within 10%) with the present work, but systematic discrepancies are observed for
149 wavelengths $< 215 \text{ nm}$. The work of *Simon et al.* [1988], *Hubrich et al.* [1977], and *Bass and*
150 *Ledford* [1976] show the largest disagreement with the parameterization developed in this work.
151 In the case of *Hubrich et al.* [1977] and *Bass and Ledford* [1976], the disagreement is more
152 random and most likely is due to the scatter in their experimental data. *Simon et al.* [1988] report
153 a CFC-11 spectrum temperature dependence that is greater than any of the other studies. (Note:
154 the *Simon et al.* CFC-11 cross section parameterization is currently recommended for use in
155 atmospheric modeling in *Sander et al.* [2011].) As discussed below, the stronger spectrum
156 temperature dependence will lead to a longer atmospheric photolysis lifetime. As shown in
157 Figure 1, significant systematic differences are observed for the spectrum temperature
158 dependence with differences of $\sim 15\%$ at 230 K and 210 nm (i.e., the most critical temperature
159 and wavelength for the atmospheric photolysis of CFC-11). The reasons for the disagreement
160 are unknown. It should also be noted that *SPARC* [2013] reports a systematic error in the

parameterization of the *Simon et al.* [1988] data as their reported spectrum parameterization does not reproduce their reported experimental data to within the quoted accuracy.

4. Atmospheric implications

The GSFC 2-D model was used to quantify the atmospheric loss processes of CFC-11 (photolysis and O(¹D) reaction) and calculate its local and global annually averaged steady-state lifetimes for year 2000 conditions. The photolytic loss of CFC-11 was evaluated in the following wavelength regions: Lyman- α (121.567 nm), 169–190, 190–230, and >230 nm. A unit photolysis quantum yield at all wavelengths was assumed in the calculations. The Lyman- α cross section, 9.8×10^{-17} cm² molecule⁻¹, and UV cross sections at wavelengths less than 190 nm and greater than 230 nm were taken from *SPARC* [2013]. Calculations were performed using three $\sigma(\lambda, T)$ parameterizations: (1) that developed in this work; (2) the parameterization given in *SPARC* [2013], which corrects a systematic error in the $\sigma(\lambda, T)$ parameterization reported in *Simon et al.* [1988]; and (3) the parameterization given in the *Sander et al.* [2011] recommendation (also referred to as *JPL10-6*), i.e., the *Simon et al.* [1988] uncorrected cross section parameterization. The O(¹D) reactive rate coefficient was taken from *SPARC* [2013]. Other kinetic and photochemical parameters were taken from *JPL10-6* unless updated in *SPARC*.

The lifetime was computed as the ratio of the annually averaged global atmospheric burden to the vertically integrated annually averaged total global loss rate [*SPARC*, 2013]. The total global lifetime can be separated by the troposphere (surface to the tropopause, seasonally and latitude-dependent), stratosphere, and mesosphere (<1 hPa) using the total global atmospheric burden and the loss rate integrated over the different atmospheric regions such that

$$\frac{1}{\tau_{\text{Tot}}} = \frac{1}{\tau_{\text{Trop}}} + \frac{1}{\tau_{\text{Strat}}} + \frac{1}{\tau_{\text{Meso}}} \quad (\text{II})$$

The 2-D model total global annually averaged lifetimes were calculated to be 58.1 ± 0.7 years for this work, $60.2 \pm \sim 6$ years for *SPARC*, and 58.6 ± 4 years for *JPL10-6* (see lifetime summary in Table 2). The significant reduction in the 2σ uncertainty range in the present work reflects the smaller CFC-11 cross section uncertainty ($\pm 4\%$) compared to the *SPARC* ($\pm 25\%$) and *JPL10-6* ($\pm 20\%$) recommendations.

We note that the absolute lifetimes computed here are somewhat greater than the recommended CFC-11 lifetime of 52 years reported in *SPARC* [2013]. The 52 year lifetime was based on a combination of: (1) derivations from various observational datasets, and (2) calculations from seven atmospheric models (including the GSFC 2-D model) which all used the *JPL10-6* recommended kinetic and photochemical parameters. Observationally based lifetimes are subject to a number of uncertainties, see e.g., *Minschwaner et al.* [2013] and *Rigby et al.*

[2013]. The absolute lifetimes computed in models are also dependent on a number of factors and associated uncertainties, including the model transport rates and the UV absorption cross sections of O₂, O₃, as well as CFC-11. The 2-D model lifetime computed using the *JPL10-6* parameters (58.6 years) is somewhat greater than the multi-model mean (55.3 years) reported in *SPARC* [2013], but is very similar to the GEOSCCM 3-D model lifetime (58.3 years). The lifetimes computed here are well within the 2σ uncertainty range (43–67 years) reported in *SPARC* [2013], which is based on the combined effect of the observational and model uncertainties. The CFC-11 lifetimes and uncertainties presented here illustrate the relative changes in these quantities as computed in one particular model due only to the different CFC-11 UV absorption cross sections (this work vs. *SPARC* vs. *JPL10-6*).

Figure 2 (left panel) shows the global annually averaged vertical profiles of the first-order photolysis and O(¹D) reactive rate coefficients (local lifetimes). CFC-11 is unreactive toward the OH radical with an estimated rate coefficient of $<1 \times 10^{-25} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ [*SPARC*, 2013], and short wavelength UV radiation only penetrates weakly into the upper-troposphere such that the tropospheric loss of CFC-11 is only a minor global loss process. The tropospheric lifetime was calculated to be ~ 1550 years (this work), ~ 1720 years (*SPARC*), and ~ 1480 years (*JPL10-6*).

Photolysis in the 190–230 nm wavelength region is the dominant loss process in the stratosphere; photolysis in this wavelength region accounts for $\sim 98\%$ of CFC-11 global loss. Figure 2 (middle and right panels) shows the calculated CFC-11 molecular loss rate and mixing ratio vertical profiles. The maximum loss rate is at 22–23 km with significant loss occurring between 18 and 28 km corresponding to temperatures approximately in the range of 208 to 225 K. Photolysis at wavelengths >230 nm is a negligible loss process throughout the atmosphere, while photolysis in the 169–190 nm range is a minor stratospheric loss process, $\sim 0.1\%$. The O(¹D) reaction is a minor loss process and accounts for $\sim 2\%$ of CFC-11 global loss. The calculated stratospheric lifetimes were 60.4 years (this work), 62.4 years (*SPARC*), and 61.0 years (*JPL10-6*). The *JPL10-6* lifetime differs from the *SPARC* value due to the correction in the *Simon et al.* [1988] cross section parameterization. Fortunately, the error in the *Simon et al.* parameterization leads to reasonable agreement between the *JPL10-6* lifetime and that reported in this work.

In the mesosphere, short wavelength UV and Lyman- α photolysis are important local loss processes (Figure 2, left panel). At altitudes >65 km, local lifetimes are relatively short, 1 day or less.

The uncertainty (range) in the calculated CFC-11 lifetime due to the uncertainty in the UV absorption cross section data, $\sigma(\lambda, T)$, and the O(¹D) rate coefficient was evaluated using the

228 2-D model. Model calculations were performed with $\sigma(\lambda,T)$ and the O(¹D) rate coefficient
229 increased to the maximum of their 2σ uncertainty limits (fast case, shorter lifetime) and the
230 minimum 2σ limit (slow case, longer lifetime) with all other model input parameters remaining
231 the same. The uncertainties in $\sigma(\lambda,T)$ were taken from this work, SPARC, and JPL10-6, while
232 the O(¹D) rate coefficient uncertainty was taken from SPARC. The calculated fast/slow
233 molecular loss rates are included in Figure 2 (middle panel) for comparison with the base case
234 calculation.

235 A comparison of the photolysis and O(¹D) reaction uncertainty contributions to the
236 overall local first-order loss rate uncertainty (2σ) as a function of altitude is given in Figure 3 for
237 this work and SPARC. The horizontal shaded region in Figure 3 highlights the altitude range
238 most critical to the atmospheric loss of CFC-11 and illustrates that UV photolysis in the 190–230
239 nm region dominates the uncertainty at these altitudes. Figure 3 also shows that the overall
240 uncertainty in the photolytic loss of CFC-11 is significantly reduced in the present work. The 2σ
241 uncertainties (range) of the calculated global annually averaged lifetimes are ± 0.7 years. This is
242 greatly reduced from the uncertainty range obtained using the previous photochemical
243 recommendations: $\sim \pm 6$ years (SPARC) and $\sim \pm 4$ years (JPL10-6).

244 The 2-D model calculations of total ozone showed minuscule changes over most of the
245 globe when using the CFC-11 cross sections presented here compared with those computed
246 using SPARC [2013]. However, minor changes of a few Dobson units were simulated during the
247 winter polar Southern Hemisphere. Further studies are needed to evaluate the impact of these
248 small changes on the computed ODPS for ODSs since CFC-11 is used as a reference compound
249 in these calculations.

250 **5. Conclusions**

251 This study reports accurate measurements of the UV absorption spectrum of CFCl₃
252 (CFC-11) as a function of temperature between 184.95 and 230 nm. On the basis of 2-D model
253 calculations, the CFC-11 cross section data presented here leads to a faster loss rate and a shorter
254 global annually averaged lifetime (58.1 years) compared to calculations using the recommended
255 cross section data using SPARC [2013] (60.2 years) and JPL10-6 [Sander *et al.*, 2011] (58.6
256 years) photochemical and kinetic recommendations. Although these lifetimes are somewhat
257 greater than the 52 year lifetime recommended in SPARC [2013], they are within the SPARC 2σ
258 uncertainty range (43–67 years), and illustrate the relative lifetime changes calculated using the
259 different cross section parameterizations.

260 The present work results in a significant reduction in the CFC-11 photolysis rate
261 2σ uncertainty, 4%, compared to 25% in SPARC and 20% in JPL10-6. The reduction in the 2σ

262 lifetime uncertainty is also significant: ± 0.7 years (this work), ± 6 years (*SPARC*), and ± 4 years
263 (*JPL10-6*). The model simulated total ozone showed minor changes in the winter polar Southern
264 Hemisphere as a result of the updated cross sections presented here, compared to *SPARC*
265 [2013], and these changes may impact the calculation of ozone depletion potentials for the
266 ozone depleting substances. Also, a decrease in the CFC-11 lifetime will decrease its global
267 warming potential (GWP). Although this work has reduced the uncertainties associated with the
268 UV absorption spectrum of CFCl_3 (CFC-11) considerably, substantial uncertainty still remains in
269 its atmospheric lifetime due to other uncertainties in observationally derived and model
270 calculated lifetimes as discussed in *SPARC* [2013].

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303 **Table 1.** CFCl₃ (CFC-11) UV Absorption Spectrum Parameterization from This Work Valid Over the
 304 Wavelength Range 190 to 230 nm for Temperatures Between 216 and 296 K.

$$\log_{10}(\sigma(\lambda, T)) = \sum_i A_i (\lambda_i - 200)^i + (T - 273) \sum_i B_i (\lambda_i - 200)^i$$

<i>i</i>	<i>A_i</i>	<i>B_i</i>
0	-18.1863	0.0002656
1	-0.0528	4.228×10^{-5}
2	-0.001126	1.4027×10^{-6}
3	-3.0552×10^{-5}	6.44645×10^{-7}
4	2.24126×10^{-6}	-3.8038×10^{-8}
5	-3.2064×10^{-8}	5.99×10^{-10}

305

306 **Table 2.** Summary of Global Annually Averaged Lifetimes and Uncertainties (Ranges) Calculated Using
 307 the GSFC 2-D Model (see text) with Input from This Work, *SPARC* [2013], and *Sander et al.* [2011].

	Lifetime (years)		
	<i>Sander et al.</i>	<i>SPARC</i>	This Work
Total	58.6 ± 4	60.2 ± 6	58.1 ± 0.7
Tropospheric	1480	1720	1550
Stratospheric	61.0	62.4	60.4
Mesospheric	$>1 \times 10^6$	$>1 \times 10^6$	$>1 \times 10^6$

308

309

310 **Figure Captions:**

311 **Figure 1.** CFCl₃ (CFC-11) UV absorption spectrum. Top: Present measurements (symbols) and
312 parameterized spectra (lines, see Table 1). Bottom: Ratio of measured values to
313 parameterization. Results from previous studies are included for comparison (see legend).

314 **Figure 2.** CFCl₃ (CFC-11) 2-D model results: Left: Global annually averaged loss rate
315 coefficient (local lifetime) and contributions (see legend). Middle: Molecular loss rate and
316 uncertainty limits; the slow and fast profiles were calculated using the 2 σ uncertainty estimates
317 in the CFC-11 UV absorption spectrum from this work. Right: CFC-11 concentration profile.

318 **Figure 3.** CFCl₃ (CFC-11) loss process contribution to the overall local uncertainty (2 σ)
319 calculated using the 2-D model (see text). Left: Results obtained from this work. Right:
320 Results obtained using model input from *Sander et al.* [2011] and updates in *SPARC* [2013].

321

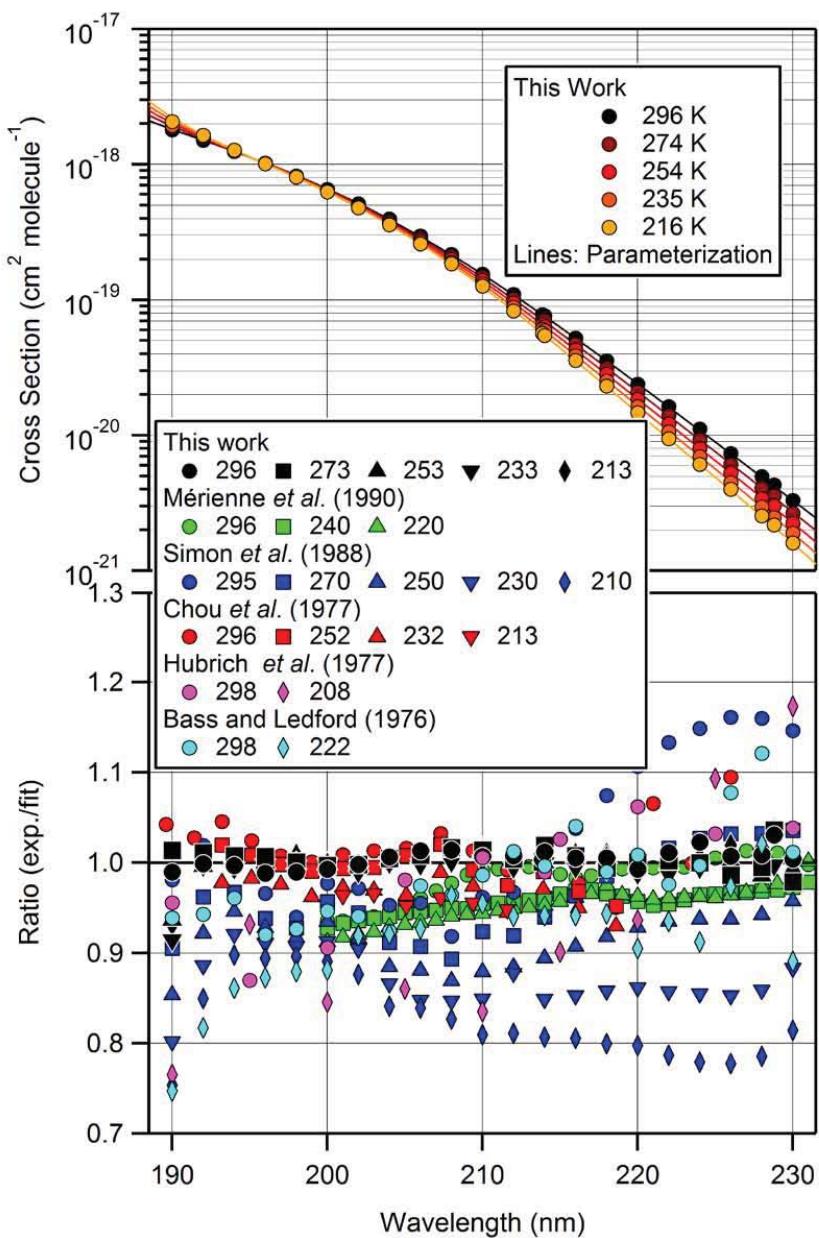


Figure 1. CFCI_3 (CFC-11) UV absorption spectrum. Top: Present measurements (symbols) and parameterized spectra (lines, see Table 1). Bottom: Ratio of measured values to parameterization. Results from previous studies are included for comparison (see legend).

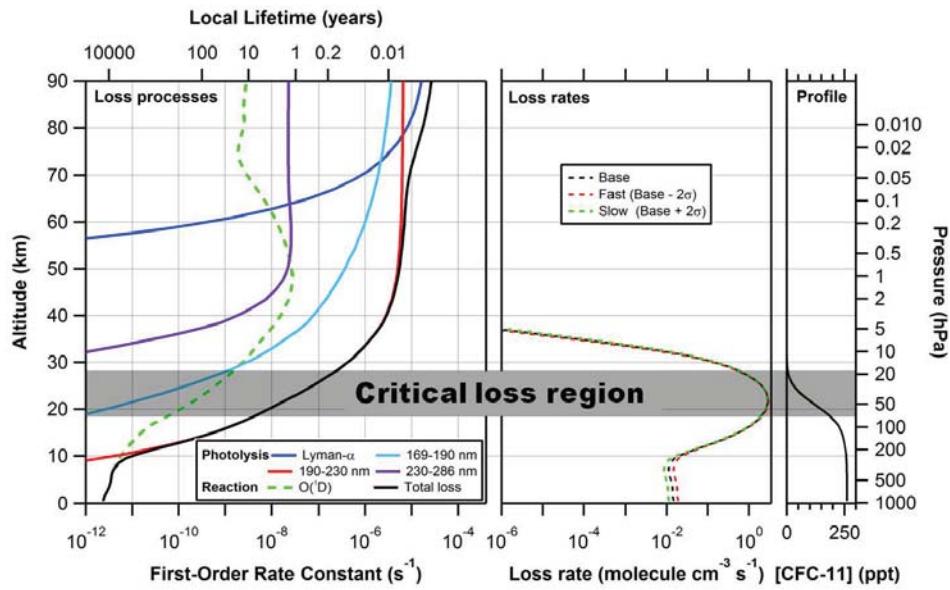


Figure 2. CFC_3 (CFC-11) 2-D model results: Left: Global annually averaged loss rate coefficient (local lifetime) and photolysis and reaction contributions (see legend). Middle: Molecular loss rate and uncertainty limits; the slow and fast profiles were calculated using the 2σ uncertainty estimates in the CFC-11 UV absorption spectrum from this work. Right: CFC-11 concentration profile.

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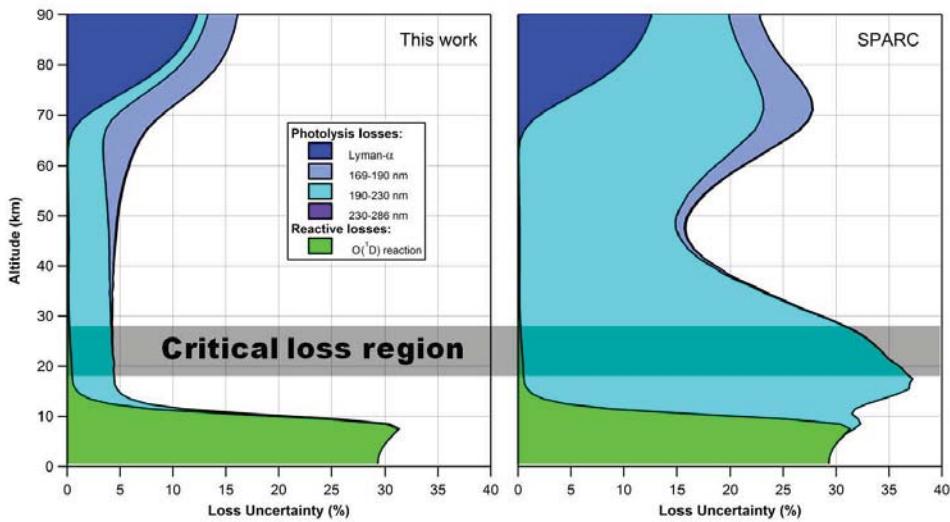


Figure 3. CFC_3 (CFC-11) loss process contribution to the overall local uncertainty (2σ) calculated using the 2-D model (see text). Left: Results obtained from this work. Right: Results obtained using model input from Sander *et al.* [2011] and updates in SPARC [2013].

325